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The Input Impedance of Common-Mode and Differential-Mode Noise Separators

K. S. Kostov,
S. Schroth,
F. Krismer,
M. Priecinsky,
H. P. Nee,
J. W. Kolar

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Konstantin S. Kostov, *Member, IEEE*, Sebastian Schroth, *Student Member, IEEE*, Florian Krismer, *Member, IEEE*,
Martin Priecinsky, *Student Member, IEEE*, Hans-Peter Nee, *Senior Member, IEEE*, and
Johann W. Kolar, *Fellow, IEEE*

***Abstract*—This paper discusses the Δ-networks and other circuits designed to separate the conducted electromagnetic interference (EMI) into its common mode (CM) and differential mode (DM) components. The input impedances of CM/DM separators must be 50 Ω resistive in the measurement frequency range, and they must be independent of the values of the noise signals and noise source impedances. The conditions for achieving such input impedances are derived. It is shown that many of the proposed separators, including the Δ-network suggested in the International Special Committee on Radio Interference (CISPR) 16-1-2 standard, do not fulfill the input impedance requirement. This leads to unreliable CM and DM measurements and, consequently, to the oversizing of EMI filters and design by trial and error.**

***Index Terms*—Common mode (CM), delta network, differential mode (DM), electromagnetic compatibility (EMC), electromagnetic interference (EMI), International Electrotechnical Commission (IEC), measurement, noise separator, power filters.**

I. INTRODUCTION

OVER THE years, there has been substantial growth not only in the amount of electronic equipment but also in its complexity, which makes modern systems more susceptible to various types of *electromagnetic interference* (EMI). These tendencies lead to a narrowing "compatibility gap" [1], which can be maintained by limiting the disturbances on the one hand and requiring a certain level of immunity on the other. Already in 1933, the *International Electrotechnical Commission* (IEC) recommended the formation of the *International Special Committee on Radio Interference* (CISPR, from Comité International Spécial des Perturbations Radioélectriques in French) to deal with the increasing *electromagnetic compatibility* (EMC) issues [2]. Since then, CISPR is the organization issuing the international standards that specify the emissions and susceptibility limits above 9 kHz [3], their methods of measurement, the equipment specifications, etc. In most countries, including the European Union, the CISPR standards have been adopted by governments and used as legal requirements for all products sold on the market. This is why manufacturers subject their products to rigorous testing and declare conformity with the limits on disturbances and other EMC regulations.

Most of today's electronic equipment and appliances cannot pass the conducted disturbance tests without an input filter that provides sufficient attenuation. For proper EMI filter design, it is crucial to know the *common mode* (CM) and *differential mode* (DM) content of the conducted emissions generated by the *equipment under test* (EUT). To ensure the repeatability of these tests, CISPR 16-1-2 [4] gives the specifications for the equipment used in such tests, such as *artificial mains networks* (AMNs), current and voltage probes, etc. According to subclause 3.4 in [4], the Δ-network should be used to separate disturbance voltages into their CM and DM parts. Unfortunately, the circuit suggested by the standard does not have the input impedance necessary for accurate CM and DM noise measurement. The same can be said for many of the noise separators proposed in the literature [5]–[17]. This paper shows what the impedance z-parameters of a single-phase CM/DM separator must be equal to in order to have the input impedances with the appropriate value and independent of the noise voltages and noise source impedances. Among the single-phase separators, only the circuits from [9], [10], [13], [16], and [17] have the required z-parameters and would give reliable CM and/or DM results, provided they are properly built and used.

The following section describes the two types of AMNs and their role in the conducted disturbance measurements. In Sections III and IV, we review various single-phase CM/DM separators found in the literature and discuss the criteria for their evaluation. Some specific requirements related to the input impedance criterion are derived in Appendixes I and II.

The theoretical analysis of various separators and measurements of the impedance characteristics of several noise separators are presented in Section V. Conclusions and suggestions are given in Section VI.

II. ARTIFICIAL MAINS NETWORKS

According to [4], there are two types of AMNs: The V-networks are used to measure the unsymmetric voltage at the mains terminals, and the Δ-networks are for measuring the symmetric or asymmetric voltages. The standard defines the

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K. S. Kostov is with Acreo Swedish ICT AB, 164 40 Kista, Sweden (e-mail: konstantin.kostov@acreo.se).

S. Schroth, F. Krismer, and J. W. Kolar are with the Swiss Federal Institute of Technology (ETH) Zurich, 8092 Zurich, Switzerland (e-mail: schroth@lem.ee.ethz.ch; krismer@lem.ee.ethz.ch; kolar@lem.ee.ethz.ch).

M. Priecinsky is with the R&D Department, Bel Power Solutions, 018 41 Dubnica nad Váhom, Slovakia (e-mail: martin.priecinsky@gmail.com).

H.-P. Nee is with the Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden (e-mail: hansi@kth.se).

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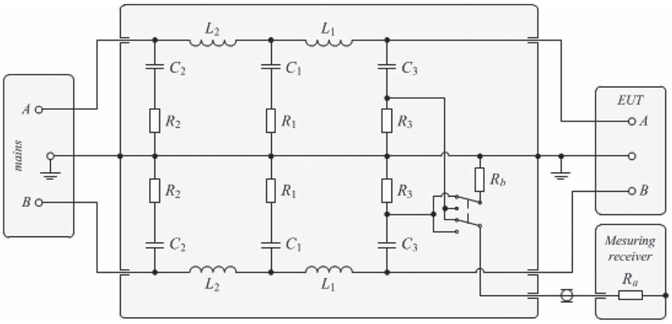


Fig. 1. V-type AMN suggested in [4]. The other V-networks suggested in the standard do not have the second filtering section ($L_2 - C_2 - R_2$).

symmetric, or DM voltage, as the "vector difference" between the voltages at two of the equipment's terminals with respect to earth. Therefore, for given phase voltages V_a and V_b at phases A and B, respectively, the DM voltage is

$$V_{\rm dm} = |\mathbf{V}_a - \mathbf{V}_b|. \tag{1}$$

A common source of confusion is that, often, DM is defined as half of the difference between the phase voltages, e.g., [2]. This would not be an issue if engineers were aware of the different definitions because the conversion to DM voltage, as defined in the standard, can be achieved simply by doubling the DM values, which in decibel scale means adding 6 dB to the measured results. Unfortunately, which definition was used in the noise separation is rarely mentioned in practice.

The asymmetric, or CM, voltage is "half of the vector sum" of the terminal voltages with respect to earth [4], which mathematically is

$$V_{\rm cm} = \frac{|\mathbf{V}_a + \mathbf{V}_b|}{2}. \tag{2}$$

The standard [4] does not consider multiphase power systems, which is one of the reasons that the three-phase noise separators proposed in [14] and [15] are not discussed in this paper.

An example of a V-type *line impedance stabilization network* (LISN) is shown in Fig. 1. Note that, although [4] suggests five V-networks and one Δ-network, it does not specify the AMN circuit. What the standard specifies is the impedance (see Fig. 2) between the LISN's earth and its phase terminals on the side of the EUT (see A and B in Fig. 1). Therefore, the manufacturers of AMNs are free to use a different circuit, as long as the impedance seen by the EUT with respect to earth has the required magnitude and phase at the specified frequencies.

Most V-LISNs available on the market have a single *radio frequency* (RF) output, at which the unsymmetric noise voltage from one of the power lines of the EUT is measured. Such AMNs cannot be used to measure CM or DM EMI because the terminal voltages must be added or subtracted *simultaneously*. There are cases where engineers measure the noise voltage from one of the lines and then the other one, i.e., performing two separate measurements, and then add or subtract the data from the two measurements. Examples of this procedure can be found also in the literature, e.g., [18]. The result, of course, is *not* the vector sum or difference of the unsymmetrical voltages, and therefore, it does not yield the CM or DM conducted emissions.

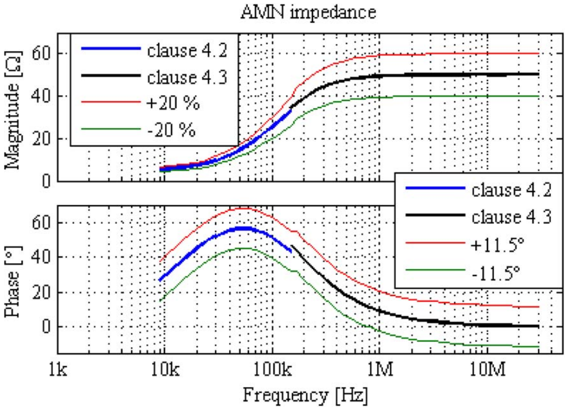


Fig. 2. AMN impedance as specified in [4]. Clause 4.2 specifies the impedance from 9 to 150 kHz, and clause 4.3 specifies the impedance from 150 kHz to 30 MHz. Both clauses allow for ±20% tolerance in the magnitude and ±11.5° tolerance in the phase of the impedance.

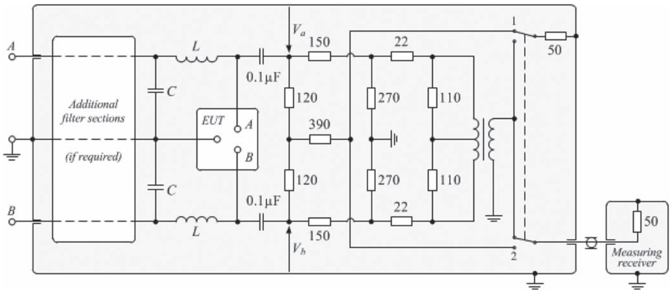


Fig. 3. 150-Ω Δ-network suggested in [4] for measuring CM or DM voltages (depending on the switch position).

III. Noise Separators

The EMI filter design usually starts by defining the CM and DM suppression requirements [18]–[21]. This is why the designer has to find a way to obtain the CM and DM noise content from the unsymmetrical noise voltages. There are many publications suggesting different noise separator circuits that use resistor networks [5], [6], *high frequency* (HF) transformers [7]–[15], op-amps [16], [17], or current probes [21]. The most natural choice, however, would be to use a CISPR-compliant Δ-type AMN because that is what should be used according to subclause 3.4 in CISPR 16-1-2. As mentioned earlier, [4] suggests only one such circuit, and it is shown in Fig. 3.

In order to identify which of the various devices actually do what they are intended to do and how well they do it, relevant evaluation criteria are necessary.

IV. Criteria for Evaluating Noise Separators

To the best of the knowledge of the authors, criteria for evaluating noise separators were first defined in [10], and they were formulated as follows:

1) low attenuation of the desired (CM or DM) signal;
2) high attenuation of the suppressed signal component;
3) linear amplitude response from 9 kHz to 30 MHz;
4) low distortion;
5) no interaction between the EUT and the LISN.

The above criteria are incomplete because they lack an input impedance requirement—one of only three requirements given in [13]; however, as will be shown next, when these three requirements are met, so will be the aforementioned five criteria. Moreover, the requirements in [13] are based on well-defined and measurable quantities for evaluation.

A. Input Impedance

To ensure the repeatability of the EMC compliance tests, the LISN must have the specified impedance (see Fig. 2) with respect to earth [4]. If the example in Fig. 1 is considered, it means that both the A and B terminals on the side of the EUT must see the specified impedance to earth. As explained in Appendix I, the HF impedance between the EUT terminals and earth is largely determined by the termination resistors (R_a and R_b). One of them is usually the input impedance of the measuring instrument, and the other may be internal for the AMN, but in any case, both terminations must be 50 Ω resistive. This applies to *all* V-type AMNs—even the RF output of the 150-Ω artificial mains V-network [4] is terminated by a 50-Ω resistor.

If the termination impedances R_a and R_b differ from one test to another, so will the measured unsymmetrical noise voltages because these are equal to the voltage drops across R_a and R_b. Thus, it would be impossible to compare the results from conducted disturbance tests, i.e., the EMC compliance test would not be repeatable, which is unacceptable. Variable termination impedances amount to changing test conditions, which leads to change in the measured unsymmetrical voltages, but then, their CM and DM components change as well. Therefore, in order to have reliable measurements of the CM and DM content of the conducted EMI, the separator *must not* change the impedance seen by the noise source, which can occur only if the input impedances of the noise separator are equal to the termination impedances of the V-type AMN, i.e., if they are 50 Ω resistive. This is shown theoretically in Appendix I.

In Appendix II, it is shown that, ideally, the input impedance requirement is satisfied when the impedance parameters of the noise separator form a diagonal matrix with all diagonal elements equal to 50 Ω and all nondiagonal entries equal to zero. In practice, due to the nonidealities, this is impossible, but the closer the impedance parameters are to the ideal values, the better a practical noise separator satisfies the input impedance requirement.

It should be noted also that, if the input impedances of the noise separator are 50 Ω resistive, i.e., if the input impedance requirement is fulfilled, so will be criterion #5 from [10]. This is because the interaction between the EUT and the LISN may change during the CM/DM voltage measurements, only if the input impedances of the noise separator differ from the terminations of the V-network used in the conducted disturbance tests.

B. Low Attenuation of the Desired Output Signal

The output voltage of the noise separator must be in accordance with the definitions for CM and DM voltage when terminated by the input of the measuring instrument. In other words, when the output(s) of the noise separator is terminated by 50-Ω resistors, the voltage across the CM output must be

$$v_{\mathrm{cm}} = \frac{|v_a + v_b|}{2} \tag{3}$$

and that across the DM output must be

$$v_{\mathrm{dm}} = |v_a - v_b|. \tag{4}$$

If the DM output of a noise separator is half of the difference of the input voltages, then adding 6 dB to the result will give the standard DM voltage as defined in (2).

How well this criterion is fulfilled can be judged from the *transmission ratio* (TR) of the desired signal, as suggested in [13]. The closer to unity (0 dB) the CMTR, the better the CM noise separation. Similarly, the closer to unity (0 dB) the DMTR, the better the DM noise separation. These TRs are numerical indicators of how well the noise separator fulfills the previously mentioned criterion #1.

C. High Attenuation of the Suppressed Output Signal

This is the requirement for low "leakage between CM and DM at the output," as defined in [13], where the CM and DM *rejection ratios* (RRs) are used to evaluate this criterion. The quality of the CM output signal is judged by the DMRR, and the quality of the DM output is judged by the CMRR. Ideally, these RRs should be zero ($-\infty$ dB), and the closer they are to the ideal value, the cleaner the output signal. Thus, the RRs of the noise separator indicate how well criterion #2 is fulfilled.

Finally, it should be noted that the closer the aforementioned TRs and RRs are to their ideal constant values, the more linear the response and the lower the distortion, i.e., they are numerical measures for criteria #3 and #4 from [10].

V. RESULTS AND DISCUSSION

In this discussion, the focus is on the input impedance criterion because, if a noise separator fails this requirement, it is not suited for its task and it is meaningless to consider the remaining performance criteria, which are evaluated from the measured TRs and RRs.

A. Theoretical Comparison of Noise Separators

Table I shows the impedance z-parameters of all passive and active single-phase noise separators known to the authors. It includes the Δ-network suggested in [4], the passive circuits proposed in [5]–[13], the active noise separators from [16] and [17], and one commercial Δ-network [22]. The HF transformers were assumed to be ideal. The ± sign in front of some values indicates the change of the corresponding z-parameter depending on the position of the switch, which some of the circuits use to set the separator for measuring CM or DM values.

Only the circuits given in [9], [10], [13], [16], and [17] fulfill the input impedance requirement because they have the impedance parameters given in (A6) in Appendix II. Their

TABLE I
SEPARATORS IMPEDANCE PARAMETERS

Separator	**z-parameters [Ω]**			
	z_{11}	z_{12}	z_{21}	z_{22}
[4]	184.41	111.37	111.37	184.41
[5],[6]	50	25	25	50
[7]	50	±31	±31	50
[8]	∞	±∞	±∞	∞
[9]-[10], [13], [16]-[17]	50	0	0	50
[11],[12]	250/3	±200/3	±200/3	250/3
[22] CM	119.12	-7.92	-7.92	119.12
[22] DM	∞	∞	∞	∞

practical performance can be objectively assessed from the measurements of their z-parameters, TRs, and RRs. The remaining noise separators in Table I do not satisfy requirement (A6), and therefore, their input impedances will not be 50 Ω resistive or will change depending on the noise source impedances and voltages.

An interesting case to consider is the first circuit given in [12], which, if measured, would give input impedances $Z_a = Z_b = 50\ \Omega$, i.e., it appears to satisfy the input impedance requirement. However, the analysis in Appendix II shows that its input impedances will depend on the input (source) voltages and on the source impedances because the nondiagonal entries of its impedance matrix are not zero. The reason to why its measured input impedances would be 50 Ω is because, when the circuit is properly terminated and when the measurement reference impedance (R_0) is 50 Ω, then, $Z_{s,a} = Z_{s,b} = R_0 = 50\ \Omega$ and, according to (A7) and (A8), the input impedances are $Z_a = Z_b = 50\ \Omega$, but that will not be the case when the source impedances are not 50 Ω. This illustrates that measuring only the input impedances is *not* sufficient to determine whether the separator satisfies the input impedance criterion.

The z-parameters in [8] and the DM configuration of [22] are infinite because they have s-parameters

$$\mathbf{S} = \begin{bmatrix} \frac{1}{3} & \frac{2}{3} \\ \frac{2}{3} & \frac{1}{3} \end{bmatrix} \tag{5}$$

and, then, the conversion equations from s- to z-parameters (see [23, p. 623]) have denominators equal to zero. When the circuit in [8] is set to measure CM, then, the sign of s_{12} and s_{21} changes to minus, which is the reason for the $-\infty$ in Table I.

B. Error Due to Improper Termination

As explained in Appendix I, changes in the termination resistors will lead to errors in the measurement of the noise voltages at each power line. Assuming that the noise current is independent of the termination resistors, the error can be evaluated as follows:

$$\text{Error, [dB]} = 20 \cdot \lg(IR) - 20 \cdot \lg(IR_0) = 20 \cdot \lg\left(\frac{R}{R_0}\right) \tag{6}$$

where I is the noise current flowing through the termination resistor R. When $R = R_0 = 50\ \Omega$, there is no error because the AMN is properly terminated. Fig. 4 shows how the error due to improper termination depends on the termination resistance.

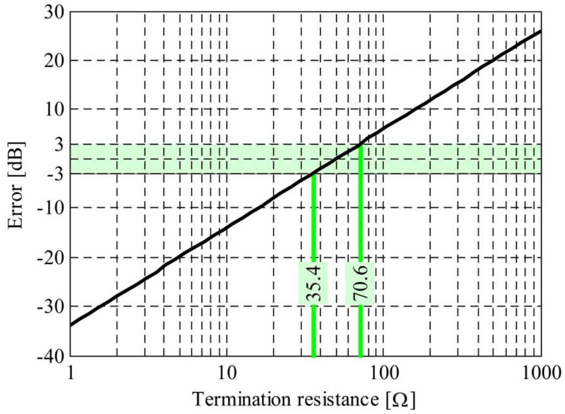


Fig. 4. Error in the measured noise voltage due to deviation of the value of the termination resistor.

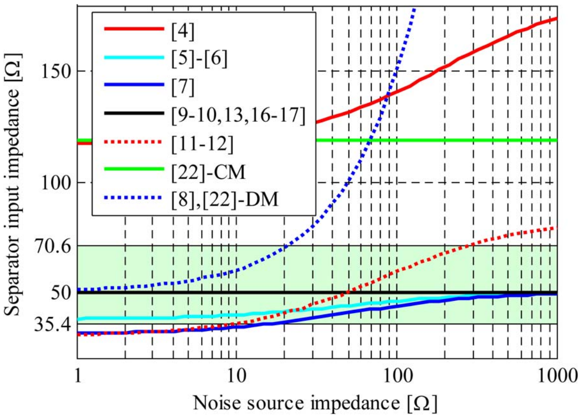
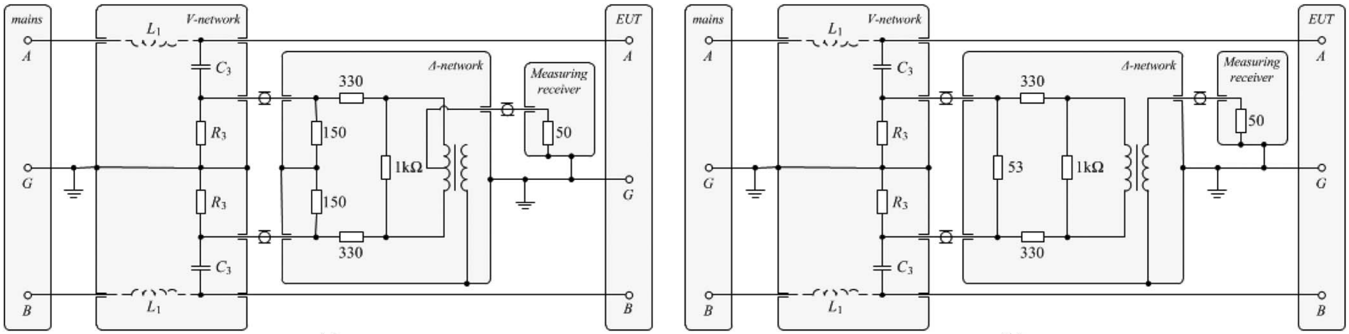


Fig. 5. Input impedance of the noise separators listed in Table I as function of the noise source impedance.

It was shown in Fig. 2 that CISPR allows for 20% tolerance in the amplitude of the AMN impedance. If the same tolerance in the termination resistors is allowed, then the termination can range between 40 and 60 Ω. According to (6), this would lead to errors ranging from -1.9 to 1.6 dB.

Alternatively, it is possible to specify the acceptable error and calculate the corresponding minimum and maximum values for the termination resistors. Assuming a permissible error of ±3 dB (see Fig. 4), it follows that the values of the terminations can be between 35.4 and 70.6 Ω. Therefore, a noise separator with input impedances below 35.4 Ω or above 70.6 Ω will lead to measurement errors exceeding 3 dB.

According to (A7) or (A8) in Appendix II, the input impedance of the noise separator at any given power line is a function of its z-parameters and the noise source impedance at the other line. Using this relationship, the input impedances of the noise separators shown in Table I are plotted in Fig. 5 as functions of the noise source impedance. The results show that the noise separators in [9], [10], [13], [16], and [17] have constant 50-Ω input impedance independent of the noise source impedance because they have impedance z-parameters in accordance with (A6). Therefore, in theory, these circuits are most suitable for separating conducted disturbances into their CM and DM components.



(a) (b)

Fig. 6. Circuit of the tested Δ-network [22]: (a) Set to measure CM and (b) set to measure DM voltage.

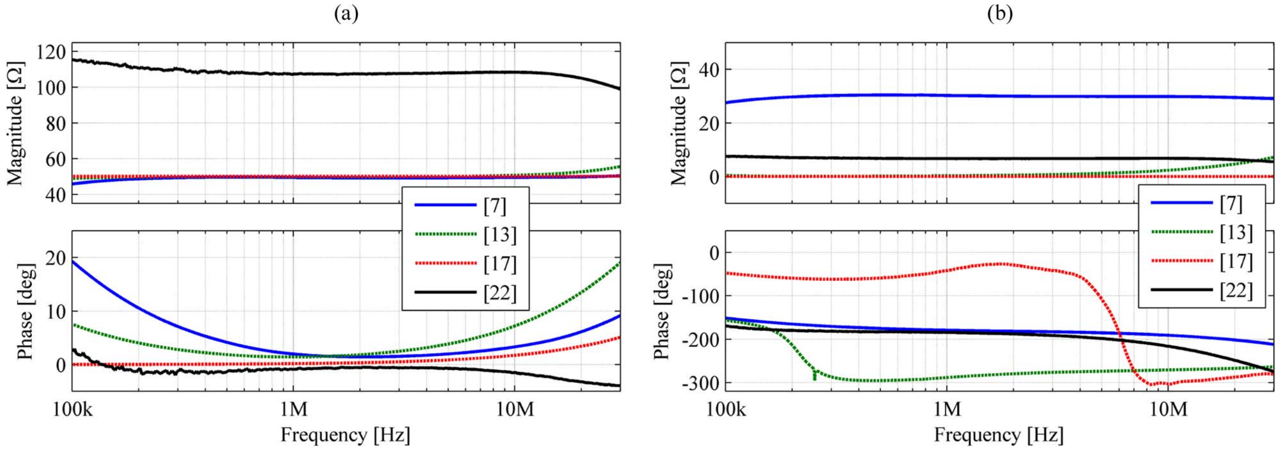


Fig. 7. Measured z-parameters of several noise separators. The circuits from [7] and [22] are set to measure CM. (a) z_{11} and z_{22} coefficients and (b) z_{12} and z_{21} coefficients.

The remaining noise separators in [4]–[8], [11], [12], and [22] have input impedances that change with the noise source impedance because the nondiagonal entries in their impedance matrices are not zero. Despite that, the resistor-based noise separator [5] might be considered suitable because its input impedance values remain within the acceptable bounds, i.e., in theory its error will not exceed 3 dB. The other advantage of the so-called *DM rejection network* (DMRN) [5] is its simplicity—it is a resistor network, without any other components; therefore, it can be very robust and can perform as expected over a wide frequency range. Unfortunately, it can measure only CM disturbances. In [6], the same DMRN is used to measure DM conducted noise by adding an HF transformer, which phase shifts one of the input signals by 180°.

Equation (A7) or (A8) are not applicable when the z-parameters are not defined, as in the case in [8] and that of the commercial Δ-network set to DM [22]. In such cases, it is useful to have an expression of the input impedance in terms of s-parameters and the impedance of the other line. It can be shown that the equivalent of (A7) or (A8) in terms of s-parameters is

$$Z_a = \frac{2R_0}{\frac{s_{12}s_{21}(R_0 - Z_{s,b})}{s_{22}(R_0 - Z_{s,b}) + R_0 + Z_{s,b}} - s_{11} + 1} - R_0 \tag{7}$$

$$Z_b = \frac{2R_0}{\frac{s_{12}s_{21}(R_0 - Z_{s,a})}{s_{11}(R_0 - Z_{s,a}) + R_0 + Z_{s,a}} - s_{22} + 1} - R_0. \tag{8}$$

When the values from (5) are inserted in (7) and (8), it turns out that the input impedances of the separator in [8] and the commercial Δ-network set to DM [22] are

$$Z_a = R_0 + Z_{s,b} \tag{9}$$

$$Z_b = R_0 + Z_{s,a} \tag{10}$$

which is the blue dotted line in Fig. 5.

In conclusion, the noise separators from [4], [7], [8], [11], [12], and [22] have input impedances that, in most cases, will differ too much from the proper AMN terminations. If used, they will change the disturbances compared to those under standard test conditions, which makes the CM/DM noise values obtained in this way inaccurate.

C. *Measurements of Z-Parameters*

In the discussion so far, the CM/DM noise separators were compared as if their components were ideal. In this section, the z-parameter measurements of several of these circuits are compared.

It is clear from the theoretical comparison that the 150-Ω Δ-network, suggested by CISPR [4], would have input impedances that vary with the input (noise) voltage and input (noise source) impedance, as shown in Appendix II and Fig. 5. Unfortunately, this circuit could not be found anywhere because, as mentioned earlier, CISPR does not specify the circuit

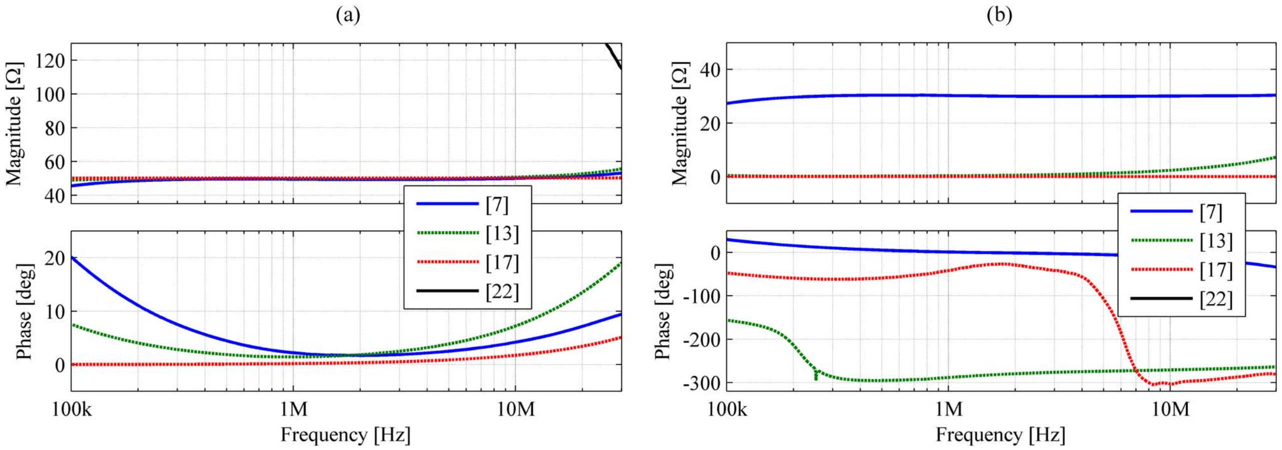


Fig. 8. Measured z-parameters of several noise separators. The circuits from [7] and [22] are set to measure DM. (a) z_{11} and z_{22} coefficients and (b) z_{12} and z_{21} coefficients.

of the AMN. The only commercial Δ-network that could be found for testing is shown in Fig. 6. It changes depending on the position of a switch. According to its documentation [22], with the switch in CM position, the circuit is shown in Fig. 6(a), and when it is set to measure DM, it changes to the circuit in Fig. 6(b).

Fig. 7 shows the measured z-parameters of the separators proposed in [7], [13], [17], and [22] set to measure CM voltage. The measurements confirm the theoretical values given in Table I. The diagonal z-parameters (z_{11} and z_{22}) are 50 Ω for [7], [13], and [17] and about 110 Ω for [22]. The nondiagonal z-parameters (z_{12} and z_{21}) are about -31 Ω (magnitude of 31 Ω and phase of 180°) for [7], 0 Ω for [13] and [17], and about -8 Ω for [22]. These measurements show that the separators from [13] and [17] meet the input impedance criteria very well over the entire frequency range. In contrast, the circuits from [7] and [22], when set to measure CM, do not fulfill the input impedance requirement.

Fig. 8 shows the measured z-parameters of the same separators, but this time, [7] and [22] are set to measure DM conducted emissions. The magnitudes of all z-parameters of the Δ-network [22] in this case are very large (exceeding 1 kΩ) and, for most frequencies, fall outside the visible range. This corroborates that the s-parameters of the circuit are such that the denominator in the equations for converting from s- to z-parameters becomes very small. For the remaining separators, the only notable difference from Fig. 7 is that, in the case in [7], the nondiagonal z-parameters (z_{12} and z_{21}) are about $+31$ Ω (this time, the phase is close to 0°). Again, the circuit from [7] and the Δ-network from [22] do not fulfill the input impedance requirement.

It is impossible to claim that all commercial Δ-type AMNs perform similarly to that in [22], but most likely, that is the case because the relevant international standard suggests a circuit that fails the input impedance requirement. If that is so, measurements of CM and DM conducted emissions, obtained with Δ-networks, must be treated with skepticism. Therefore, the designers of EMI filters must build their own noise separators by choosing one of the circuits proposed in the literature. Based on the aforementioned analysis, the appropriate circuits can be found in [9], [10], [13], [16], and [17].

VI. CONCLUSION

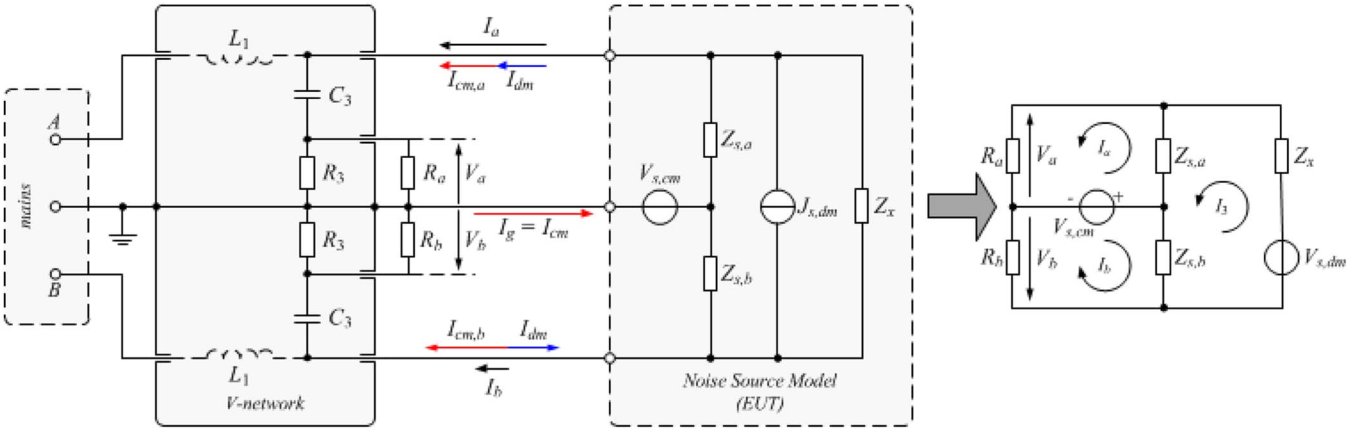
In this paper, it has been shown that Δ-networks and other circuits for separating unsymmetrical signals into their CM and DM components must have impedance matrices with diagonal entries equal to 50 Ω resistive and nondiagonal entries equal to zero. If this condition is not met, the input impedances of the CM/DM separator will deviate from the required value, and they will depend on the noise voltages and noise source impedances. CM and DM conducted emissions measured with noise separators that fail this requirement are unreliable. Without accurate data for the CM and DM noise levels, designers have no choice but to oversize their filters in order to ensure sufficient attenuation of both noise components. If they could use noise separators that provide accurate CM and DM data, they would be able to improve their designs.

The analysis of the single-phase noise separators proposed in the literature shows that only the circuits in [9], [10], [13], [16], and [17] fulfill the input impedance requirement. One of the remaining circuits, the DMRN from [5], can measure the CM conducted disturbance with less than 3-dB error. Given its simplicity and the lack of nonlinear magnetic components, it can be considered as a viable option when the DM conducted emissions are not a concern.

The Δ-network suggested by CISPR for measuring CM and DM disturbance voltages fails the input impedance requirement. Therefore, it is proposed to change the Δ-network suggested by CISPR in the future revisions of their standards. Meanwhile, EMI filter designers should treat CM and DM measurements with skepticism and consider how these were obtained.

APPENDIX I

In EMC compliance testing, the EUT is supplied via a V-type AMN like in Fig. 1 or similar. Fig. 9(a) represents the noise source acting on a single-phase V-network with the corresponding noise currents and the unsymmetrical noise voltages



(a) (b)

Fig. 9. (a) Circuit diagram of the noise source model connected to a V-type AMN and (b) its simplified HF equivalent.

V_a and V_b, appearing across the termination resistors R_a and R_b, which should be 50 Ω.

The value of R_3 is 1 kΩ, which is much larger than that of the termination resistors. The value of C_3 in the V-networks suggested in [4] is 0.1 μF or 0.25 μF, which corresponds to an impedance of less than 10 Ω at 150 kHz and falls with the frequency. On the other hand, the impedance of L_1 rises with the frequency. This is how the LISN couples the HF disturbances from the EUT and decouples them from the power line. It is usually assumed that the noise source sees only the termination resistors connected to ground. To simplify the following analysis, the same assumption is made, and the circuit reduces to the one shown in Fig. 9(b), for which it is found that

$$\begin{bmatrix} Z_{s,a}+R_a & 0 & -Z_{s,a} \\ 0 & Z_{s,b}+R_b & Z_{s,b} \\ -Z_{s,a} & Z_{s,b} & Z_{s,a}+Z_{s,b}+Z_x \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_3 \end{bmatrix} = \begin{bmatrix} V_{s,\mathrm{cm}} \\ V_{s,\mathrm{cm}} \\ V_{s,\mathrm{dm}} \end{bmatrix}. \tag{A1}$$

By definition, the CM voltage is

$$V_{\mathrm{cm}} = \left| \frac{\mathbf{V}_a + \mathbf{V}_b}{2} \right| = \left| \frac{I_a R_a + I_b R_b}{2} \right|. \tag{A2}$$

After solving I_a and I_b from (A1) and inserting the CM voltage in (A2), (A4) is found to be a function of both source voltages ($V_{s,\mathrm{dm}}$ and $V_{s,\mathrm{cm}}$) and source impedances (Z_x, $Z_{s,a}$, and $Z_{s,b}$), as well as the termination impedances R_a and R_b.

Similarly for the DM voltage,

$$V_{\mathrm{dm}} = |\mathbf{V}_a - \mathbf{V}_b| = |I_a R_a - I_b R_b| \tag{A3}$$

and after inserting I_a and I_b, the result is (A5).

Equations (A4) and (A5), shown at the bottom of the page, show that the CM and DM noise voltages depend on the noise source voltages,noise source impedances, and the termination resistors. If the termination resistors vary from test to test, so will the results. Even if the noise source would be symmetric, i.e., even if it could be assumed that $Z_{s,a} = Z_{s,b}$, the repeatability of the results cannot be guaranteed. Only when $R_a = R_b$ is constant and does not change from test to test can the results be repeatable, provided that the parasitics that determine the noise source impedances are similar. Setting $R_a = R_b = R_0 = 50\ \Omega$ in (A4) and (A5) simplifies the expressions for CM and DM voltages and shows that they depend only on the noise source voltages and impedances, which are the same for a given EUT, and therefore, the measurements are repeatable. It is interesting to note that, in the case of an EUT with symmetrical noise source impedance, i.e., $Z_{s,a} = Z_{s,b}$, (A4) and (A5) are further simplified, and it can be seen that the measured CM voltage (V_{cm}) does not depend on the DM source voltage ($V_{s,\mathrm{dm}}$) and the measured DM voltage (V_{dm}) does not depend on the CM source voltage ($V_{s,\mathrm{cm}}$).

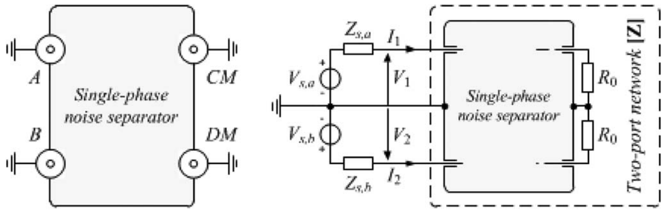
Strictly speaking, the parasitics, which determine the noise source impedances (Z_x, $Z_{s,a}$, and $Z_{s,b}$) of any two different EUTs, cannot be equal, but they are similar in all samples of the same product. Therefore, the compliance tests of a given product can be repeatable within certain tolerance bounds.

APPENDIX II

A single-phase noise separator has two input ports and one or two output ports [see Fig. 10(a)], but because the outputs are terminated by 50-Ω resistors, we may view the separator as a two-port network [see Fig. 10(b)].

$$V_{\mathrm{cm}} = \frac{1}{2} \left| \frac{V_{s,\mathrm{cm}} \left\{ R_b \left[(R_a + R_b) Z_a + (R_b + Z_b) Z_x \right] + \left(R_b^2 - R_a^2 \right) Z_b \right\} + V_{s,\mathrm{dm}} \left[(R_a + R_b) Z_a + R_a^2 \right] (R_b + Z_b)}{R_a R_b (Z_a + Z_b + Z_x) + (R_a + R_b) Z_a Z_b + (R_a Z_b + R_b Z_a) Z_x + Z_a Z_b Z_x} \right| \tag{A4}$$

$$V_{\mathrm{dm}} = \left| \frac{V_{s,\mathrm{cm}} \left\{ R_b \left[(R_a - R_b) Z_a - (R_b + Z_b) Z_x \right] - \left(R_a^2 + R_b^2 \right) Z_b \right\} + V_{s,\mathrm{dm}} \left[(R_a - R_b) Z_a + R_a^2 \right] (R_b + Z_b)}{R_a R_b (Z_a + Z_b + Z_x) + (R_a + R_b) Z_a Z_b + (R_a Z_b + R_b Z_a) Z_x + Z_a Z_b Z_x} \right| \tag{A5}$$



(a) (b)

Fig. 10. Single-phase noise separator (a) as a black box and (b) as a two-port network, when its outputs are properly terminated with 50-Ω resistors.

In order to satisfy the input impedance requirement, the impedance z-parameters of the noise separator must be

$$\mathbf{Z} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} = \begin{bmatrix} R_0 & 0 \\ 0 & R_0 \end{bmatrix}. \tag{A6}$$

If condition (A6) is not met, the input impedances of the noise separator will depend on the noise source impedances and noise voltages, which are shown next.

A. Source Impedance Dependence

The input impedance at the first input port [see Fig. 10(b)] is

$$Z_a = z_{11} - \frac{z_{12} z_{21}}{z_{22} + Z_{s,b}} \tag{A7}$$

and the input impedance at the second port [see Fig. 10(b)] is

$$Z_b = z_{22} - \frac{z_{12} z_{21}}{z_{11} + Z_{s,a}}. \tag{A8}$$

Therefore, at least one of z_{12} and z_{21} must be zero in order to have input impedances independent of the source impedances. When (A6) is met, each one of the input impedances is independent of the source impedance at the other port.

B. Voltage Dependence

Starting from the definition of z-parameters

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{A9}$$

the port currents I_1 and I_2 can be expressed in terms of z-parameters and port voltages

$$I_1 = \frac{\begin{vmatrix} V_1 & z_{12} \\ V_2 & z_{22} \end{vmatrix}}{\det(\mathbf{Z})} = \frac{z_{22} V_1 - z_{12} V_2}{\det(\mathbf{Z})} \tag{A10}$$

$$I_2 = \frac{\begin{vmatrix} z_{11} & V_1 \\ z_{21} & V_2 \end{vmatrix}}{\det(\mathbf{Z})} = \frac{z_{11} V_2 - z_{21} V_1}{\det(\mathbf{Z})}. \tag{A11}$$

Then, the input impedances are

$$Z_1 = \frac{V_1}{I_1} = \frac{V_1 \det(\mathbf{Z})}{z_{22} V_1 - z_{12} V_2} \text{ and } Z_2 = \frac{V_2}{I_2} = \frac{V_2 \det(\mathbf{Z})}{z_{11} V_2 - z_{21} V_1}. \tag{A12}$$

From (A12), it is clear that the only way to make both input impedances independent from the input voltages is to have $z_{12} = z_{21} = 0$.

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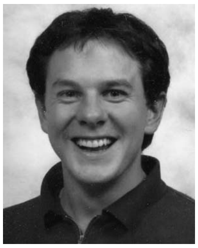
Konstantin S. Kostov (S'05–M'09) received the M.Sc., Lic.Sc., and D.Sc. (Tech.) degrees in electrical engineering from Helsinki University of Technology, Espoo, Finland, in 2003, 2006, and 2009, respectively.

In 2011, he moved to Stockholm, Sweden, for a two-year postdoctoral position with the Department of Electrical Energy Conversion, Royal Institute of Technology (KTH). Since September 2013, he has been a Research Scientist with the Department of Nanoelectronics, Acreo Swedish ICT, Kista, Sweden. His research interests include the design, modeling, and control of power electronic converters, electromagnetic compatibility in power electronics, and packaging of high-power semiconductor devices.

Sebastian Schroth (S'13) was born in Schwäbisch Hall, Germany, on September 7, 1985. He received the Diploma degree in electrical engineering and information technology from the University of Stuttgart, Stuttgart, Germany. During his studies, he focused on power electronics, control system, and electrical drives. During his Diploma thesis, he designed and realized a PMSM for a special control algorithm.

He has been working in the Power Electronic Systems Laboratory, Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, since September 2011, with a focus on electromagnetic interference.



Florian Krismer (S'05–M'12) received the M.Sc. degree from the University of Technology Vienna, Vienna, Austria, in 2004 and the Ph.D. degree from the Power Electronic Systems Laboratory (PES), Swiss Federal Institute of Technology (ETH) Zürich, Zürich, Switzerland, in 2011.

He is currently a Postdoctoral Fellow with the PES, ETH Zürich. His research interests include the analysis, design, and optimization of high-current and high-frequency power converters.

Martin Priecinsky (S'11) received the M.Sc. and Ph.D. degrees from the Faculty of Electrical Engineering, University of Žilina, Slovakia, in 2009 and 2012, respectively. The scope of his research during his Ph.D. studies was control techniques for power converters with high switching frequency. In 2011 he was with Aalto University, Helsinki, Finland, where he focused on EMC in power electronics.

He is currently a member of R&D Department at Bel Power Solutions, Dubnica nad Váhom, Slovakia.

Hans-Peter Nee (S'91–M'96–SM'04) was born in Västerås, Sweden, in 1963. He received the M.Sc., Licentiate, and Ph.D. degrees in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 1987, 1992, and 1996, respectively.

In 1999, he was appointed Professor of power electronics at KTH, where he currently serves as the Head of the Electrical Energy Conversion Laboratory. His current research interests include power electronic converters, semiconductor components, and the control aspects of utility applications, such as flexible ac transmission systems and high-voltage dc transmission, and variable-speed drives.

Prof. Nee was the recipient of the Energy Prize from the Swedish State Power Board in 1991, the International Conference on Electrical Machines (Paris) Verbal Prize in 1994, the Torsten Lindström Electric Power Scholarship in 1996, and the Elforsk Scholarship in 1997. He is a member of the European Power Electronics and Drives Association, involved with the Executive Council and the International Scientific Committee. He is also an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS and was on the Board of the IEEE Sweden Section for several years, serving as its Chairman during 2002–2003.

Johann W. Kolar (S'89–M'91–SM'04–F'10) received the M.Sc. and Ph.D. degree (*summa cum laude/promotio sub auspiciis praesidentis rei publicae*) from the University of Technology Vienna, Vienna, Austria.

He is a Full Professor in Power Electronics at the Swiss Federal Institute of Technology (ETH) Zurich, Zürich, Switzerland, and the Chair of the ETH Power Electronic Systems Laboratory. He has proposed numerous novel converter topologies and modulation/control concepts, e.g., the VIENNA Rectifier, the Swiss Rectifier, and the three-phase ac–ac sparse matrix converter. In this context, he has published over 450 scientific papers in conference proceedings, over 180 papers in international journals, and two book chapters, and has filed more than 110 patents. The focus of his current research is on ac–ac and ac–dc converter topologies with low effects on the mains, solid-state transformers for smart microgrids, ultracompact and ultraefficient converter modules employing the latest power semiconductor technology (SiC and GaN), power supply on chip systems, multiobjective optimization, and ultrahigh-speed and bearingless motors. In the course of his research, he has supervised over 50 Ph.D. and Postdoctoral students.

Dr. Kolar was the recipient of 19 IEEE TRANSACTIONS and Conference Prize Paper Awards. He initiated and/or is the founder/cofounder of four ETH spin-off companies. He is a member of the steering committees of several leading international conferences in the field and has been serving as an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and IEEE TRANSACTIONS ON POWER ELECTRONICS.